Appendix D

Vertical Stratification and the Pycnocline

The *pycnocline* has a functional role in defining designated use boundaries. The definitions of the designated use boundaries take into account the types and needs of the living resources that inhabit different parts of the Chesapeake Bay, as well as the bathymetry, hydrology, physical features, and natural stratification of the Chesapeake Bay waters as described in Chapter IV.

STRATIFICATION

Vertical stratification is foremost among the physical factors affecting dissolved oxygen concentrations in some parts of Chesapeake Bay and its tidal tributaries. Stratification arises from differences in water density within the water column due to vertical differences in salinity and temperature of the source waters feeding into Chesapeake Bay tidal waters and the extent of their vertical mixing. The water coming into Chesapeake Bay and its tidal tributaries from the land via the tributaries is fresh while water from the ocean is saline. In the summer period, the water coming from the land is also warmer than ocean water. Colder water is more dense than warmer water, and saline water is more dense than fresh. The simple model is that the less dense freshwater moves seaward over the layer of more dense seawater moving from the mouth of Chesapeake Bay northward. An idealized example is shown in Figure D-1. To the extent that the two (or more) layers remain self-contained and poorly mixed, the waters are stratified. If the density discontinuity is great enough to prevent mixing of the layers and constitutes a vertical barrier to diffusion of dissolved oxygen, then a pycnocline is said to exist.

When physical features like channels, holes and sills inhibit lateral exchange of waters and a pycnocline inhibits vertical exchange, oxygen that is consumed in biological respiration or other oxygen-consuming processes in the imprisoned subpycnocline waters can not be replenished. When there is no barrier to lateral exchange, the effect of the pycnocline on lower layer oxygen levels may be ameliorated. For this reason, the extent of isolation caused by a pycnocline, as well as the frequency of formation and the depth of the pycnocline when present are factors to be considered in defining designated use boundaries.

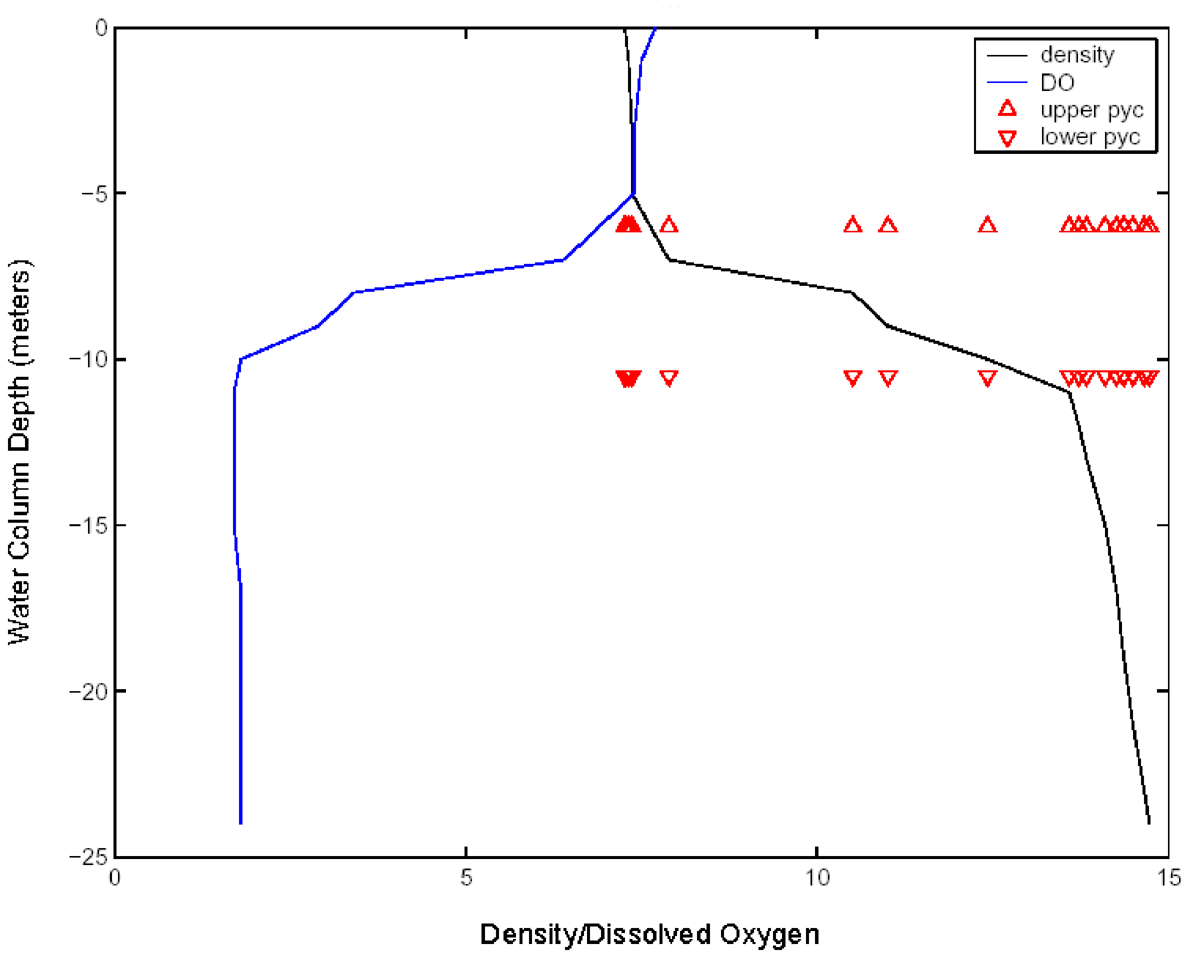

Figure D-1. Illustration of stratification of the water column in the mainstem of the Chesapeake Bay.

Source: Chesapeake Bay Program website http://www.chesapeakebay.net/data.htm.

CALCULATING PYCNOCLINE DEPTH

Density Gradient Threshold

The threshold for the density gradient that defines the upper pycnocline depth ($0.1\ kg/m^4$) is taken from Fisher, et al, in review. The density gradient sufficient to stop turbulent mixing for any water body is somewhat determined by the local physical processes in that body. Density gradient thresholds vary by water body. Fisher, et al determined the Chesapeake Bay upper pycnocline threshold by examining existing literature for other oceanic and estuarine systems and applying those methods to the Chesapeake Bay. Determination of this number involved examining thousands of vertical plots of density, dissolved oxygen concentration, and the vertical slopes of these two parameters to find a reasonable threshold value. The value of $0.1\ kg/m^4$ was judged to be most reasonable value for the upper pycnocline depth in the Chesapeake Bay and is in line with values for other estuarine systems. The actual pycnocline depths were not overly sensitive to the threshold value chosen, since mixed layer gradients tend to be much less than $0.1\ kg/m^4$ and inter-pycnocline gradients tend to be much greater than $0.1\ kg/m^4$.

Using similar methods, the value of $0.2\ kg/m^4$ was chosen as the lower pycnocline depth gradient by the monitoring data analysis team at the Chesapeake Bay Program Office. Vertical density and dissolved oxygen concentration plots from around the Chesapeake Bay and its tidal tributaries were examined to determine the threshold value that was most representative of the density gradient defining the upper boundary of the lower mixed layer, when and where it existed. The upper layer density threshold of $0.1\ kg/m^4$ was judged to be too low as it sometimes placed the lower pycnocline depth at levels that did not have a large effect on the dissolved oxygen concentration.

Pycnocline Calculation Methodologies

The Chesapeake Bay Program Water Quality Monitoring Program collects vertical profiles of temperature, salinity, and conductivity measurements (among other parameters) at 1 to 2 meter intervals at each of its sampling stations. From these measurements, there are at least two approaches for determining a pycnocline.

Vertical Density Profile

The upper and lower pycnocline depths can be determined by constructing a vertical density (sigma_t) profile and applying an absolute density change threshold. This is the method used for all pycnocline calculations in this document and is recommended for application by the states in defining designated use boundaries. For a detailed explanation of the derivation of this method see Fisher (2003).

1) Calculate density using the following equations:

```
temp c    =   water temperature in degrees Celsius

sigo      =   –0.069+((1.47808*((salinity-0.03)/1.805))
              (0.00157*(((salinity–0.03)/1.805)**2))
              +0.0000398*(((salinity–0.03)/1.805)**3)));

tsum      =   (–1*(((tempc-3.98)**2)/503.57))*
              ((tempc+283)/(tempc+67.26));

sa        =   (10**–3)*tempc)*(4.7867-
              (0.098185*tempc)+(0.0010843*(tempc**2)));

sb        =   ((10**–6)*tempc)*(18.030–
              (0.8164*tempc)+(0.01667*(tempc**2)));

Sigma_t   =   tsum+((sigo+0.1324)*(1–sa+sb*(sigo –0.1324)));
```

2) Apply the following rules to the density profile:
   - i) From the water surface, the first density slope observation that is greater than 0.1 kg/m^4 is designated as the upper pycnocline depth provided that:
     - a) That observation is not the first observation in the water column; and
     - b) The next density slope observation below is positive.
   - ii) From the bottom, the first density slope observation that is greater than 0.2 kg/m^4 is designated as the lower pycnocline depth provided that:
     - a) An upper pycnocline depth exists;
     - b) There is a bottom mixed layer, defined by the first or second density slope observation from the bottom being less than 0.2 kg/m^4; and
     - c) The next density slope observation above is positive.

Vertical Differences in Conductivity

A 'working' pycnocline depth can be calculated using vertical differences in conductivity. The following is the Chesapeake Bay Water Quality Monitoring Program field method applied during water quality monitoring sampling cruises for determining the presence of a pycnocline and, if one or more exist, the depth of the upper and lower boundary and, therefore, depths at which to collect water samples for chemical analysis in the laboratory.

1) Find the average rate of change from surface to bottom: i.e., subtract surface conductivity from bottom conductivity and divide by the depth.

2) Multiply the average rate of change by 2. This is called the *threshold.*

3) If the threshold is less than 500, then it is determined that no pycnocline exists at the site.

4) It the threshold is 500 or greater, then each interval from surface to bottom is checked to determine if the difference from one meter to the next is greater than or equal to the threshold. The upper pycnocline is defined as the first encounter of a difference that exceeds the threshold and the upper pycnocline depth is set at one-half the depth interval distance. For example, if the threshold is first exceeded between 4 and 5 meters, then the pycnocline is set at 4.5 meters.

5) Then the process is reversed and each interval from bottom to surface is checked. If the threshold is exceeded at a depth more than 1.5 meters from the upper pycnocline, then a second pycnocline is said to exist and the lower pycnocline depth is set at one-half the depth interval distance, as before.

Table D-1 provides some statistics on the frequency of occurrence, depth of pycnoclines, and the distance between upper and lower pycnoclines in spring and summer at locations throughout the Chesapeake Bay and its tidal tributaries. The statistics are for each Chesapeake Bay Water Quality Monitoring Program station over the period analyzed for the allocations process 1985–1994. (See the Chesapeake Bay Program website at http://www.chesapeakebay.net for a map of these stations.)

Table D-1. Chesapeake Bay Water Quality Monitoring Program stations median pycnocline depths and percent occurrence: 1985-1994.

Station	Depth	Upper Depth	Interpyc depth	Lower Depth	Upper Percent	Lower Percent
CB1.1	6.1	-	-	-	0%	0%
CB2.1	6.0	2.3	-	-	17%	0%
CB2.2	12.1	4.0	2.8	6.9	68%	20%
CB3.1	12.8	2.9	5.0	7.9	99%	76%
CB3.2	11.7	2.9	4.2	7.1	93%	57%
CB3.3C	23.7	4.2	10.6	14.8	100%	88%
CB3.3E	8.2	2.6	1.6	4.2	80%	18%
CB3.3W	9.0	2.7	2.3	5.0	77%	13%
CB4.1C	31.8	5.6	11.7	17.3	100%	96%
CB4.1E	23.1	6.5	7.8	14.3	99%	84%
CB4.1W	9.1	3.4	2.6	5.9	56%	19%
CB4.2C	26.8	6.9	9.6	16.5	100%	98%
CB4.2E	9.3	4.1	2.1	6.2	65%	13%

Station	Depth	Upper Depth	Interpyc depth	Lower Depth	Upper Percent	Lower Percent
CB4.2W	9.3	4.3	1.2	5.5	46%	11%
CB4.3C	25.9	6.5	8.6	15.2	100%	94%
CB4.3E	22.1	7.1	7.8	14.8	97%	86%
CB4.3W	9.7	4.4	1.2	5.6	51%	10%
CB4.4	29.4	6.6	10.3	16.9	100%	100%
CB5.1	33.3	6.4	8.6	15.0	100%	99%
CB5.1W	9.1	4.4	-	-	24%	0%
CB5.2	29.5	7.5	9.0	16.6	100%	100%
CB5.3	26.2	6.1	7.2	13.2	100%	96%
CB5.4	32.6	5.3	12.8	18.1	100%	97%
CB5.4W	5.3	2.5	1.0	3.5	29%	3%
CB5.5	19.5	4.7	8.4	13.1	99%	79%
CB6.1	13.1	4.5	4.3	8.7	100%	80%
CB6.2	11.2	4.3	3.3	7.6	96%	76%
CB6.3	12.8	3.7	4.5	8.1	97%	87%
CB6.4	10.3	3.3	3.3	6.6	90%	54%
CB7.1	25.2	4.8	9.7	14.5	85%	65%
CB7.1N	31.7	5.9	12.5	18.4	69%	35%
CB7.1S	16.1	3.8	5.5	9.3	96%	87%
CB7.2	22.1	3.4	9.0	12.4	97%	95%
CB7.2E	13.4	3.2	3.7	6.9	88%	72%
CB7.3	13.8	3.3	5.8	9.1	96%	81%
CB7.3E	17.8	4.1	6.1	10.2	93%	73%
CB7.4	13.9	3.2	5.3	8.5	95%	79%
CB7.4N	12.9	3.3	3.9	7.3	74%	44%
CB8.1	9.8	3.5	3.7	7.2	95%	38%
CB8.1E	17.9	4.3	6.2	10.5	96%	82%
EBE1	8.4	3.2	1.8	5.0	61%	9%
EBE2	9.0	2.5	-	-	100%	0%
EE1.1	12.3	6.6	2.6	9.2	74%	31%
EE2.1	7.8	3.3	1.4	4.7	53%	12%

Station	Depth	Upper Depth	Interpyc depth	Lower Depth	Upper Percent	Lower Percent
EE2.2	13.1	5.0	3.6	8.6	72%	49%
EE3.0	7.1	2.8	-	-	12%	0%
EE3.1	13.2	4.1	2.5	6.6	60%	16%
EE3.2	26.8	6.9	10.7	17.6	42%	9%
EE3.3	3.9	1.5	-	-	19%	0%
EE3.4	4.7	2.0	0.5	2.5	26%	4%
EE3.5	27.3	7.0	8.7	15.7	41%	19%
ELI1	8.0	3.5	-	-	100%	0%
ELI2	13.5	5.9	4.9	10.8	87%	30%
ELI3	12.0	3.5	6.0	9.5	100%	100%
ET1.1	2.9	-	-	-	0%	0%
ET10.1	5.2	-	-	-	0%	0%
ET2.1	13.2	4.0	-	-	3%	0%
ET2.2	2.9	-	-	-	0%	0%
ET2.3	12.3	4.5	-	-	8%	0%
ET3.1	5.3	-	-	-	0%	0%
ET4.1	5.4	1.8	-	-	5%	0%
ET4.2	13.9	5.4	4.4	9.8	70%	43%
ET5.1	5.7	2.0	-	-	8%	0%
ET5.2	11.8	3.7	3.4	7.1	76%	20%
ET6.1	5.0	1.5	-	-	3%	0%
ET6.2	3.8	1.5	-	-	49%	0%
ET7.1	7.7	2.3	0.6	2.9	71%	14%
ET8.1	5.1	1.7	2.8	4.5	31%	3%
ET9.1	4.8	1.5	1.0	2.5	11%	6%
LAF1	5.2	2.5	-	-	40%	0%
LE1.1	12.1	4.8	2.7	7.5	75%	25%
LE1.2	17.1	5.7	3.9	9.6	68%	16%
LE1.3	23.3	7.3	5.3	12.6	43%	9%
LE1.4	14.9	7.5	3.0	10.5	44%	4%
LE2.2	11.2	3.4	3.7	7.1	91%	64%

Station	Depth	Upper Depth	Interpyc depth	Lower Depth	Upper Percent	Lower Percent
LE2.3	19.7	5.7	7.4	13.1	95%	77%
LE3.1	5.5	4.0	-	-	34%	0%
LE3.2	12.2	6.2	2.2	8.4	73%	43%
LE3.3	4.1	4.0	-	-	3%	0%
LE3.4	11.3	6.6	3.7	10.2	72%	23%
LE3.6	9.9	3.9	2.5	6.4	81%	30%
LE3.7	7.4	3.7	1.3	5.0	52%	8%
LE4.1	7.5	4.3	1.7	6.0	60%	6%
LE4.2	11.6	4.8	3.0	7.8	51%	17%
LE4.3	14.3	7.0	5.1	12.1	66%	39%
LE5.1	6.6	4.7	1.3	6.0	24%	1%
LE5.2	7.6	4.2	2.0	6.3	79%	10%
LE5.3	6.3	4.0	2.0	6.0	68%	3%
LE5.4	13.7	5.4	6.6	12.0	44%	13%
LE5.5	21.2	5.1	10.5	15.6	96%	73%
LE5.6	13.7	7.0	5.0	12.0	71%	16%
MAT0016	6.8	-	-	-	0%	0%
MAT0078	1.0	-	-	-	0%	0%
PIS0033	1.0	-	-	-	0%	0%
RET1.1	11.1	4.7	2.8	7.5	64%	9%
RET2.1	7.3	-	-	-	0%	0%
RET2.2	9.8	5.1	1.9	7.0	22%	2%
RET2.3	9.2	-	-	-	0%	0%
RET2.4	15.7	5.4	5.4	10.8	79%	33%
RET3.1	5.2	4.0	-	-	12%	0%
RET3.2	4.0	-	-	-	0%	0%
RET4.1	4.5	4.0	-	-	1%	0%
RET4.2	10.9	7.1	0.9	8.0	18%	1%
RET4.3	4.7	4.0	-	-	4%	0%
RET5.1	1.1	-	-	-	0%	0%
RET5.1A	2.8	-	-	-	0%	0%

Station	Depth	Upper Depth	Interpyc depth	Lower Depth	Upper Percent	Lower Percent
RET5.2	7.5	4.9	-	-	15%	0%
SBE1	14.0	3.5	-	-	100%	0%
SBE2	12.5	4.4	4.9	9.3	83%	43%
SBE3	11.0	2.5	5.0	7.5	100%	100%
SBE4	12.0	2.5	-	-	100%	0%
SBE5	11.0	3.6	3.5	7.1	100%	70%
TF1.2	1.0	-	-	-	0%	0%
TF1.3	1.0	-	-	-	0%	0%
TF1.4	1.2	-	-	-	0%	0%
TF1.5	10.5	-	-	-	0%	0%
TF1.6	6.0	-	-	-	0%	0%
TF1.7	2.9	1.8	-	-	5%	0%
TF2.1	19.0	-	-	-	0%	0%
TF2.2	8.3	-	-	-	0%	0%
TF2.3	12.8	-	-	-	0%	0%
TF2.4	8.9	-	-	-	0%	0%
TF3.1A	2.9	-	-	-	0%	0%
TF3.1B	2.9	-	-	-	0%	0%
TF3.1C	4.0	-	-	-	0%	0%
TF3.1D	2.7	-	-	-	0%	0%
TF3.1E	2.8	-	-	-	0%	0%
TF3.2	6.1	-	-	-	0%	0%
TF3.2A	4.0	-	-	-	0%	0%
TF3.3	5.7	4.2	-	-	14%	0%
TF4.1A	5.8	-	-	-	0%	0%
TF4.2	5.9	-	-	-	0%	0%
TF4.4	2.7	-	-	-	0%	0%
TF4.4A	6.3	-	-	-	0%	0%
TF5.2	1.0	-	-	-	0%	0%
TF5.2A	7.0	-	-	-	0%	0%
TF5.3	9.8	-	-	-	0%	0%

Station	Depth	Upper Depth	Interpyc depth	Lower Depth	Upper Percent	Lower Percent
TF5.4	5.8	-	-	-	0%	0%
TF5.5	8.2	-	-	-	0%	0%
TF5.5A	7.4	-	-	-	0%	0%
TF5.6	8.5	6.0	-	-	1%	0%
TF5.6A	7.8	-	-	-	0%	0%
WBE1	4.7	2.8	-	-	17%	0%
WE4.1	6.1	2.9	0.7	3.6	35%	9%
WE4.2	14.5	6.3	4.2	10.5	86%	35%
WE4.3	6.0	2.8	0.8	3.5	20%	1%
WE4.4	7.6	2.3	1.5	3.8	19%	4%
WT1.1	2.3	-	-	-	0%	0%
WT2.1	2.0	-	-	-	0%	0%
WT3.1	3.3	1.5	-	-	5%	0%
WT4.1	1.8	-	-	-	0%	0%
WT5.1	14.5	3.6	7.7	11.3	100%	69%
WT6.1	5.4	2.5	1.0	3.5	57%	5%
WT7.1	8.6	3.1	2.4	5.4	87%	31%
WT8.1	8.6	2.2	1.7	3.8	91%	58%
WT8.2	2.9	1.5	-	-	2%	0%
WT8.3	3.3	1.5	-	-	15%	0%
WXT0001	1.1	-	-	-	0%	0%
XFB1986	1.5	-	-	-	0%	0%
XGG8251	5.5	2.5	-	-	8%	0%